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AN OPTIMAL CONTROLLER DESIGN FOR AN AUTONOMOUS UNDERWATER VEHICLE MODEL

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Abstract: *This study designs a controller that are used in an AUV for depth and direction changing system. This design is based on the linearized model of the underwater vehicle.*

Introduction

In the article it is present a development of the control systems for depth and direction changing, system which is considered to be decoupled from the entire system of the underwater vehicle control.
To obtain diving equations of motion the logical first step is to start with the general equations of motion. Finally the article is based on optimal depth and pitch controller synthesis [1] and simulation of the nonlinear model and controller of the underwater vehicle.

Model of the underwater vehicle

The nonlinear model consists in 12 differential equations which describe 6 translations and 6 rotations.
Also, here are presented the model with numerical values for the hydrodynamic coefficients which belong to the underwater vehicle used for simulations and controller synthesis from [1].
The final part consists in the open loop simulations for the complete nonlinear model of the vehicle.
In fig.1 the underwater vehicle with 4 fins used in the study and the 2 coordinate frames (rigid body frame and earth frame) is presented:

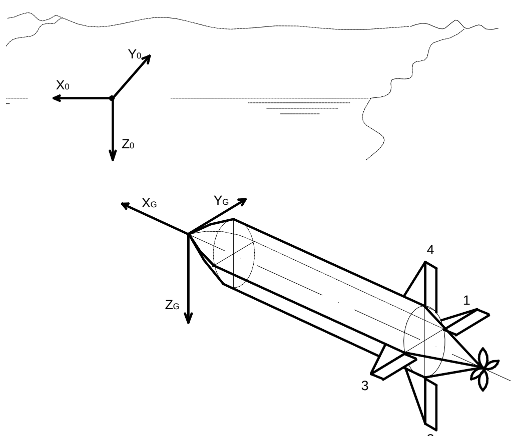

Figure 1 Underwater vehicle with 4 fins

The nonlinear equations of underwater vehicle motions are:

$$m\left[\dot{u} + qw - rv - x_G\left(q^2 + r^2\right) + y_G\left(pq - \dot{r}\right) + z_G\left(pr - \dot{q}\right)\right] = X$$
$$m\left[\dot{v} + ru - pw - y_G\left(r^2 + p^2\right) + z_G\left(qr - \dot{p}\right) + x_G\left(qp + \dot{r}\right)\right] = Y$$
$$m\left[\dot{w} + pv - qu - z_G\left(p^2 + q^2\right) + x_G\left(rp - \dot{q}\right) + y_G\left(rq + \dot{p}\right)\right] = Z \quad (1)$$

$$I_x\dot{p} + \left(I_z - I_y\right)qr + m\left[y_G\left(\dot{w} + pv - qu\right) - z_G\left(\dot{v} + ru - pw\right)\right] = K$$
$$I_y\dot{q} + \left(I_x - I_z\right)rp + m\left[z_G\left(\dot{u} + qw - rv\right) - x_G\left(\dot{w} + pv - qu\right)\right] = M$$
$$I_z\dot{r} + \left(I_y - I_x\right)pq + m\left[x_G\left(\dot{v} + ru - pw\right) - y_G\left(\dot{u} + qw - rv\right)\right] = N \quad (2)$$

From these equations the matrix form is:

$$M_{RB}\dot{v} + C_{RB}(v)v = \tau_{RB}$$
(3)

where:
M_{RB} – inertial matrix;
C_{RB} – coriolis forces and centripetal forces of rigid body matrix;
τ_{RB} – forces and moments vectors of rigid body.
Further, we can present the other form of the equations (3):

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau$$
(4)

where

$$M = M_{RB} + M_A;\ C(v) = C_{RB}(v) + C_A(v)$$
(5)

M_A – adherent masses forces matrix;
C_A – coriolis forces and centripetal forces of adherent masses forces matrix;
D(v) – total matrix of damping forces;
τ – propulsion forces and moments.
The nonlinear model of the underwater vehicle is numerically linearized in 3 different equilibrium points, specific for the operational characteristics of the underwater weapon systems.
These points are:
a)
- Forward speed 3m/s
- Thrust force 416N
- Depth 4m

b)
- Forward speed 4m/s
- Thrust force 1000N
- Depth 4m

c)
- Forward speed 5m/s
- Thrust force 2000N
- Depth 4m

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The linearized forms for these equations are:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -M^{-1}[C(t)+D(t)] & -M^{-1}G(t) \\ J(t) & J^*(t) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} M^{-1} \\ 0 \end{bmatrix} u \quad (6)$$

$$\dot{x} = A(t)x + B(t)u \quad (7)$$

The controllers design

Starting with the linearised form of movement equations, we consider that, the command vector δ being formed by the angles from the four fins and the external forces and moments.

The linearized equation will become:

$$\dot{x} = A(t)x + B(t)B^{+}[\delta \quad u_1]^T \quad (8)$$

where:

$\delta = [\delta_1 \quad \delta_2 \quad \delta_3 \quad \delta_4]^T$ - the fins angles vector;

$u_1 = [X \quad Y \quad Z \quad K \quad M \quad N]^T$ - the external forces and moments vector.

The 12[th] order derived linearized model, for each equilibrium point, is unstable, the system having 6 eigenvalues with positive real part.

For the synthesis of the new depth and trajectory optimal controller, the derived linearized model is decoupled. The resulting model has 8 states (depth, pitch, speed forward, heave speed, pitch speed, yaw, sway speed, yaw speed) and four inputs (fin's angles), which also is unstable having 5 eigenvalues with positive real parts.

In the final part of the chapter a new "feedforward-feedback" control system is synthesized, shown in fig.2.

The controller K is an optimal linear regulator (LQR) and the feedforward controller K_f is the pseudoinverse of the transfer function as in the standard setpoint control.

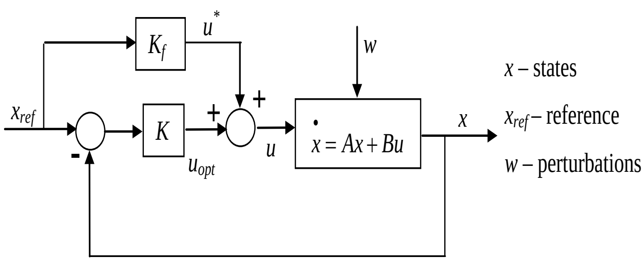

Figure 2. "Feedforward-feedback" control system

For the linear model derived for the first equilibrium point the two controllers are:

$$K = \begin{pmatrix} 0.70711 & -1.7944 & -0.005954 & 1.2043 & -0.56117 & -2.2759 & -0.3353 & -0.41263 \\ 4.57E-16 & 2.34E-15 & -6.58E-17 & 2.44E-15 & -1.97E-17 & -8.572 & -0.71333 & -1.4079 \\ -0.70711 & 1.7944 & 0.0059543 & -1.2043 & 0.56117 & -2.2759 & -0.3353 & -4.13E-01 \\ -2.35E-17 & -5.14E-16 & 4.04E-17 & -7.24E-16 & 3.39E-17 & 4.0202 & 0.042738 & 5.83E-01 \end{pmatrix} \quad (9)$$

$$K_f = \begin{pmatrix} 0,0000 & -0,1773 & 0,0015 & -0,5282 & 0,0493 & 0,0000 & -0,1275 & 0,8523 \\ 0,0000 & 0,0000 & 0,0000 & 0,0000 & 0,0000 & 0,0000 & 0,5851 & -0,9886 \\ 0,0000 & 0,1773 & -0,0015 & 0,5282 & -0,0493 & 0,0000 & -0,1275 & 0,8523 \\ 0,0000 & 0,0000 & 0,0000 & 0,0000 & 0,0000 & 0,0000 & -0,8402 & 2,6932 \end{pmatrix} \quad (10)$$

The actuator model implements both the continuous and discrete control laws. The discrete control law is derived from the continuous law, with the upper bound of 30° for the fin angle and a threshold of 15°.

The simulation of the nonlinear model

In this paragraph were made the simulations of the complete nonlinear model of the underwater vehicle with the controllers synthesized. The simulations are referring to depth and trajectory control, in the presence of external disturbances. The simulation results present the controlled states and the control inputs for both, the continuous and discrete controllers.

The simulink model of the autonomous underwater vehicle from [1] is presented in fig. 3.

The depth and trajectory (yaw) simulations for the controllers synthesized for the second point of equilibrium, are presented in below figures (4 - 7):

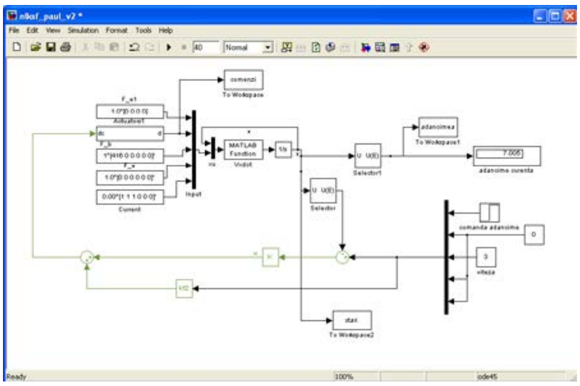

Figure 3. The closed loop scheme for the underwater vehicle

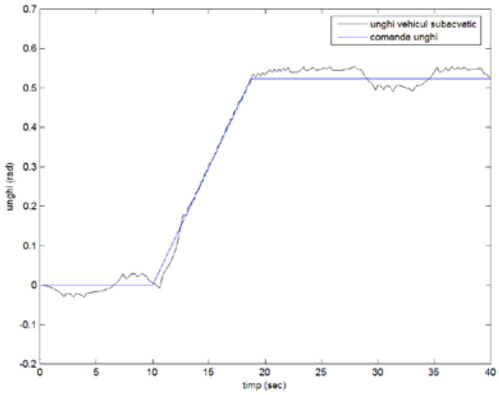

Figure 4 Depth and depth reference for continuous control

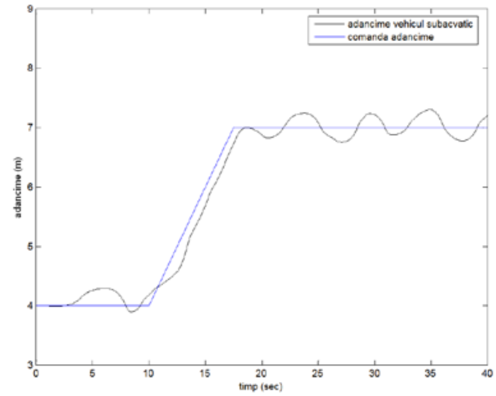

Figure 6 Depth and depth reference for discrete control

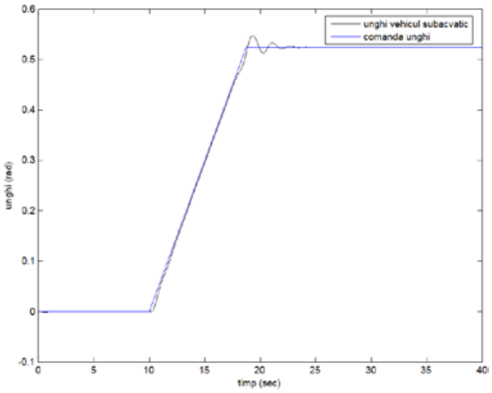

Figure 5 Yaw angle and yaw angle reference continuous control

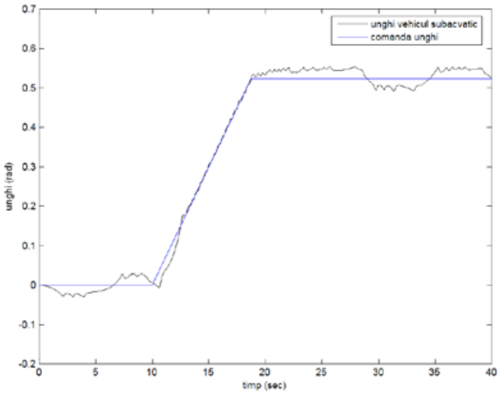

Figure 7 Yaw angle and yaw angle reference discrete control

CONCLUSION

The System is not total decoupled so this was the reason for using an optimal controller. Analyzing those all simulations from the article and from the bibliographic reference [1] we can consider that, the system dynamic doesn’t depend totally from the depth and pitch.

This system can be easily implemented in such areas as military domain, marine exploration domain etc.

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